Design and Simulation of An Intelligent Laser Tracking System

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Design, Simulation and Implementation of Intelligent high power Laser Tracking System

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Abstract— **Laser tracking systems (LTS) are used for detecting and tracking the targets in the battlefield by obtaining the position information of these targets which is being designated and illuminated by an Airborne or Ground-based laser designator then the laser light reflected from these targets and come to the input of the optical systems of the laser seeker. An optical system for collimating the reflected beam from the target is one of the main components of the laser tracking system (LTS), the Quad Detector (QD) as a part of this optical system is simply consists of four photodiodes capable of detecting light spot projected on its surfaces and determine the deviation position of the laser spot from its center then converts the incident laser spot to its corresponding photocurrent, the readout circuit that filter and convert the photocurrent to its corresponding voltage and the tracking system that is controlling the laser seeker movement to track the intended target based on the feedback information of the QD depending on the real position of the tracking platform.**

The main objective of this paper is to design, simulate and implement an intelligent laser tracking system (LTS) that was described in details involving three major areas, design and simulation of an electrical interfacing read out circuitry of QD, design and construction of the Laser optical seeker system, design and construction of the fuzzy logic control hardware and software. This fuzzy logic controller (FLC) is a branch of artificial intelligence that deals with approximate reasoning algorithms used to emulate human thinking and decision making in machines. It was planned for the sensor control algorithm to use a proportional–integral–derivative (PID) like fuzzy logic controllers (FLC) to improve the control performance for a system with noise, a relatively long time of response and the rate of change of this movement depending on how far is the spot located from the center of QD surface.

Index Terms— **Laser tracking system, Quad detector, fuzzy control, target tracking.**

I. Introduction

Laser tracking systems (LTS) are used for detecting and tracking the targets in the battlefield by obtaining the position information of these targets which is being designated and illuminated by an Airborne or Ground-based laser designator then the laser light reflected from these targets and come to the input of the optical systems of the laser seeker.

One of the main components of the laser tracking system (LTS) is the optical system for collimating a reflected beam from the target, the Quad Detector (QD) which is simply consists of four photodiodes capable of detecting light spot projected on its surfaces and determine the deviation position of the laser spot from its center then converts the incident laser spot to its corresponding photocurrent, the readout circuit that filter and convert the photocurrent to its corresponding voltage, the tracking system that is controlling the laser seeker movement to track the intended target based on the feedback information of the QD depending on the real position of the tracking platform and the laser target designation system which is a laser light source used to designate a target. The beam used in target designation is invisible, a series of coded pulses of laser-light are fired. These signals bounce off the target into the sky, where they are detected by the seeker on the laser guided munitions, It is extremely difficult for people being targeted to tell whether they are being marked or not, some vehicles and aircraft are equipped with a laser warning receiver that can tells whether they are being laser designated by others or not. Laser designators work best in clear atmospheric conditions. Cloud cover, rain or smoke can make reliable designation of targets difficult or even impossible. For getting an accurate guidance of a LTS, It is required to get a high performance control algorithm to quickly guide the seeker with the incoming laser reflected from targets enabling the targets to be effectively tracked and attacked. Laser tracking systems are divided into active and semi-active laser (SAL) tracking systems. In Active LTS all the components of the system are in the same missile, while in the semi active LTS the illumination of the target is performed with a separate laser source (laser designator)[1].

After studying the different techniques of the laser target tracking systems from point of accurate tracking, the SAL guidance was chosen that it’s the most widely

technique as the target can be illuminated and designated with a laser spot by either airborne or ground-based laser designator which is utilized on the modern battlefield for multiple weapon systems ranging from rockets to missiles to guided bombs.

In order to get an intelligent tracking system, an algorithm of the microcontroller uses the fuzzy logic to improve the controlling process and so improving the tracking performance of the two servo motors which are used in the tracking platform.

A need for an accurate intelligent tracking system in order to precisely guide munitions (AGM, smart weapon and smart munitions) to precisely hit specific targets and to minimize damage to things other than the target not allowing even if some free missiles or bombs miss thus the harm to civilians and so the amount of collateral damage may be somewhat reduced. The challenge is to design a more stable high performance intelligent LTS with a fast response to the sudden fast movement and transform free unguided missiles into laser guided missiles.

One of the main objectives of this paper is to design an intelligent LTS that use a fuzzy logic controller (FLC) which is a branch of artificial intelligence that deals with approximate reasoning algorithms used to emulate human thinking and decision making in machines. It was planned for the sensor control algorithm to use a proportional–integral–derivative (PID) like fuzzy logic controllers (FLC) to improve the control performance for a system with noise, a relatively long time of response and the rate of change of this movement depending on how far is the spot located from the center of QD surface. That's happened by getting the feedback position from the QD all the time during its movement. It was planned for the motion control circuit to use Arduino Duo microcontroller to control the servo motors for LTS. Implementation of the fuzzy logic algorithm that works with 32 bits of precision has been done by using Software codes uploaded from the computer to the microcontrollers by the USB interface. It was designed in a way that uses the pulse width modulation (PWM) technique to give the servo motors the right angle to move. Also it was essential to send a feedback from the sensors to the controller, as an example, the four quadrants of the QD sensor and the motors feedback signals to ensure that the right exact movement was achieved.

The main objective of this paper is to design, simulate and implement an intelligent laser tracking system (LTS) that was described in details involving three major areas, design and simulation of an electrical interfacing read out circuitry of QD, design and construction of the Laser optical seeker system, design and construction of the fuzzy logic control hardware and software.

II. POSITION SENSITIVE DEVICE (PSD)

A Position Sensitive Detector (PSD) and/or Position Sensitive Device is an optical position sensor (OPS), that can measure a position of a light spot in one or two-dimensions on a sensor surface by providing an analog output current proportional to the displacement of the centroid of a light spot that hits the sensitive area of the device. Essentially, a PSD is a PIN diode that is sandwiched between two conductive layers connected to 4 electrodes, two by two.

A. *Segmented PSD*

Segmented PSD's, are common substrate photodiodes divided into either two or four segments (for one or two-dimensional measurements, respectively), separated by a gap or dead region as shown in "Fig. 1". A symmetrical optical beam generates equal photocurrents in all segments, if positioned at the center. The relative position is obtained by simply measuring the output current of each segment. They offer position resolution better than 0.1 µm and accuracy higher than lateral effect PSD's due to superior responsivity match between the elements. Since the position resolution is not dependent on the signal to noise ratio of the system, as it is in lateral effect PSD's, very low light level detection is possible. Segmented PSDs have a higher accuracy level than the lateral effect PSDs, due to the superior responsibility match between the elements. They exhibit excellent stability over time and temperature and fast response times necessary for pulsed applications. They are however, confined to certain limitations, such as the light spot has to overlap all segments at all times and it cannot be smaller than the gap between the segments. It is important to have a uniform intensity distribution of the light spot for correct measurements. They are excellent devices for applications like nulling, beam centering and laser spot tracking.[2]

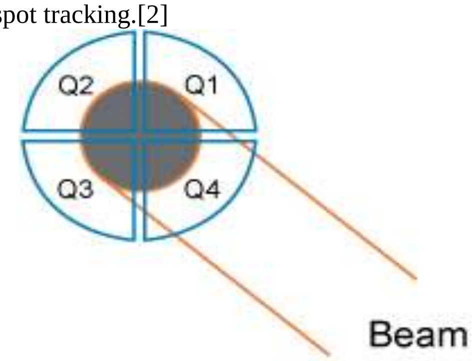

Figure 1. Position Segmented Position Sensitive Detector.

The sensor is used for positioning by measuring each segment's photocurrent. A symmetrical beam is positioned at the center of the PSD if all these currents are equal[2]. A segmented PSD's resolution is independent of the signal to noise ratio (S/N) of the system, enabling them to detect very low light levels. This group of PSDs is limited though, since the beam spot must be bigger than the dead region and must also overlap all the segments at all times and a uniform beam spot intensity is also required[2]. For example, if the beam only falls on the two upper segments, only the spot's X position can be determined. A displacement of more than 10% of the beam diameter will also cause the measurement to become non-linear. These limitations

restrict the beam spot displacement measurements to a small and narrow the tracking range[3].

B. *Lateral effect PSD*

Lateral effect PSD's, are continuous single element planar diffused photodiodes with no gaps or dead areas as shown in "Fig. 2". These types of PSD's provide direct readout of a light spot displacement across the entire active area. This is achieved by providing an analog output directly proportional to both the position and intensity of a light spot present on the detector active area. A light spot present on the active area will generate a photocurrent, which flows from the point of incidence through the resistive layer to the contacts. This photocurrent is inversely proportional to the resistance between the incident light spot and the contact. When the input light spot is exactly at the device center, equal current signals are generated. By moving the light spot over the active area, the amount of current generated at the contacts will determine the exact light spot position at each instant of time. These electrical signals are proportionately related to the light spot position from the center. The main advantage of lateral-effect diodes is their wide dynamic range. They can measure the light spot position all the way to the edge of the sensor. They are also independent of the light spot profile and intensity distribution that affects the position reading in the segmented diodes. The input light beam may be any size and shape, since the position of the centroid of the light spot is indicated and provides electrical output signals proportional to the displacement from the center. The devices can resolve positions better than 0.5 µm. The resolution is detector/circuit signal to noise ratio dependent.

OSI Optoelectronics manufactures two types of lateral effect PSDs which are the Duo-Lateral and the Tetra-Lateral structures. Both structures are available in one and two-dimensional configurations.

In duo-lateral PSD's, there are two resistive layers one at the top and the other at the bottom of the photodiode. The photocurrent is divided into two parts in each layer. This structure type can resolve light spot movements of less than 0.5 µm and have very small position detection error, all the way almost to the edge of the active area. They also exhibit excellent position linearity over the entire active area. The tetra-lateral PSD's own a single resistive layer in which the photocurrent is divided into two or four parts for one or two dimensional sensing respectively. These devices exhibit more position non linearity at distances far away from the center, as well as larger position detection errors compared to duo-lateral types[2]. The duo-lateral type has the highest position detecting ability, but is also the most expensive. The pincushion type is an improved tetra-lateral PSD, as it has a bigger high linearity region than the tetra-lateral type PSD. Both of these though have a simpler bias scheme, smaller dark current and faster response time than the duo-lateral type.

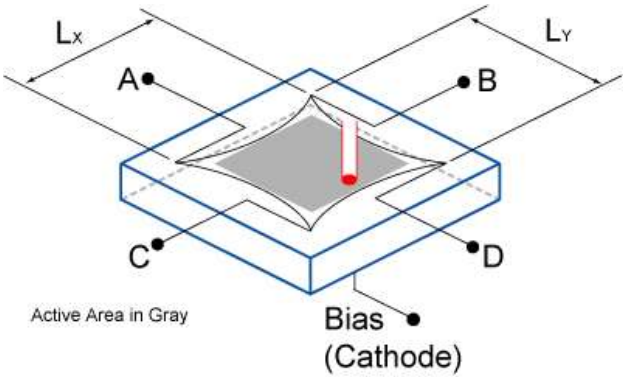

Figure 2. Lateral Effect Position Sensitive Detector

Lateral effect photodiodes have the main advantage of a wide dynamic range and that the measured position is independent of the light spot intensity distribution (unlike segmented PSDs), the resolution however is detector (or circuit) signal to noise ratio dependent [2].

Finally, Table I shows a comparison between the two types of PSDs.

TABLE I. COMPARISON BETWEEN THE TWO TYPES OF PSD

	Lateral effect	Segmented
Position resolution	0.5 µm	0.1 µm
light spot profile	Independent	Dependent
S/N ratio of the system	Dependent	Independent (very low light level detection)
Accuracy	Lower	Higher (excellent stability over time, temperature and fast response time necessary for pulsed applications)

III. CHARACTERIZATION AND MODULATION OF HIGH POWER DIODE LASER MODULE (HPDLM) AS A LASER DESIGNATOR

Experimental studies on characterization of a high power diode laser module as a laser target designator source (LTD) used in the tracking system including the (I-V) characteristic, output optical power verses drive electrical current, slope efficiency, the laser beam profile and the wavelength dependence of temperature. Like all practical designation and tracking system, a modulation of a high power laser source with pulse repetition frequencies (PRF) mode of operation is required so the effect of different frequencies on both of the pulse to pulse stability and wavelength stability are measured, analyzed and investigated.

On the modern battlefield, Semi-Active Laser (SAL) guidance is used to guide bombs and missiles toward them targets. Airborne or ground-based laser designators

are the keys which this SAL guidance depends on to illuminate the target for the artilleries with laser reflected energy. This reflected light from the target is then sensed by the seeker on the weapon system, typically containing a quadrant photo detector.

This information is then processed, using the guidance system to determine the required corrections and computes miss angles. In this sense, SAL seekers provide a terminal homing capability, based upon laser energy being reflected from the target, in such geometry, the in-coming radiation is detected and used for the guidance process[4]. Maverick, Copperhead, and Hellfire missiles entered the service in the late 1970's, These weapon systems equipped with SAL homing seekers, this type of laser is invisible operating at a wavelength of 1.06 micros, which is being used and further developed today, these types of seekers do not emit the laser energy, they passively detect and track the reflected laser beam being illuminated by an external designator because the weapon system does not have a laser source installed[4].

For those munitions using a laser seeker, an intelligent control system is needed to quickly guide the seeker with incoming laser reflected from targets to be tracked because of an accurate guidance of Air to Ground missiles (AGM) and bombs is needed to hit the right targets, It requires a high performance control algorithm to guide them to the intended targets, also it's important to use a coded laser designator with pulse repetition frequency (PRF) in order to guide many munitions in the same scene with different targets without interference.

The light amplification by stimulated emission of radiation (laser) is the enabling technology of more precise weapons. Laser systems enable joint forces to engage a wider range of targets with more accuracy and fewer munitions than previously possible[5].

Laser designators emit a narrow beam of laser pulses which is susceptible to degradation from atmospheric scatter and a variety of target reflections[5].

Laser designators and seekers use a pulse coding system to ensure that a specific seeker and designator combination work in harmony. By setting the same code in both the designator and the seeker, the seeker will track only the energy with the correct coding. The pulse coding is based on pulse repetition frequency (PRF) [5].

Illustrates IR and laser equipment compatibility is shown in "Fig. 3" As depicted, compatibility exists only between Laser target detection systems (LTDs) and Laser Spot Tracking systems (LSTs). In other words, all coded laser target designators can work with all coded laser acquisition and/or spot trackers and all coded laser-guided weapons. IR pointers and night vision goggles (NVGs) are only compatible with each other.IR pointers cannot designate for LSTs, and NVGs cannot see the LTD mark. Forward-looking infrared (FLIR) systems are not compatible with LTDs, LSTs, and/or IR pointers[5].

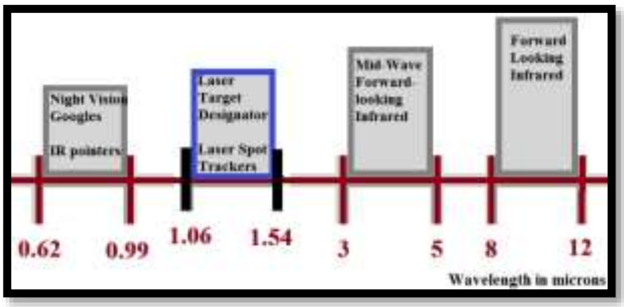

Figure 3. Infrared Electromagnetic Spectrum

A. Electrical Characterization of the High power Diode Laser Module

1) Experimental setup

A high power diode laser fiber coupled module model (VDM00231) operating at 980 ± 2 nm which has a maximum CW output power up to 4 W under maximum input driving current at 7 A, an integrated highly precise temperature controller model (UM series DiTec, Jenoptik) used for driving diode lasers in CW or pulsed mode as it has an On-Board Oscillator which can be freely configure for pulsating the laser, power supply (output 24V, 10.5A) and a fiber cable are used to measure the electrical characterization of the high power diode laser module as shown in "Fig. 4".

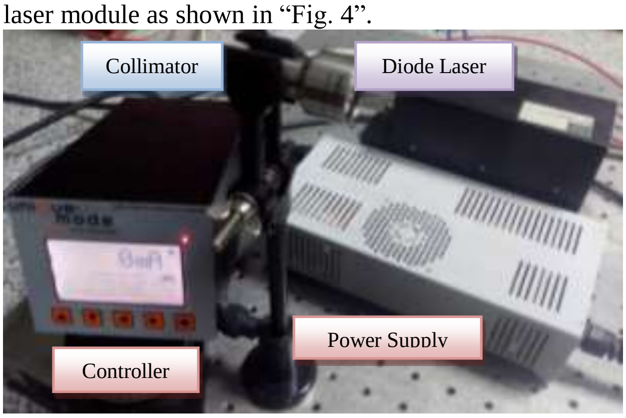

Figure 4. The photograph of the diode laser system

The highest brightness is achieved by transforming the asymmetric radiation from the laser diode into a symmetrical beam, using micro optics and finally this beam can be coupled into 125µm fiber with core diameter of 50 µm.

2) Electrical Measurements Results

By adjusting the laser diode driver to different currents then obtaining the driving input voltages of the diode module (measured and viewed through the controller screen) at different operating temperatures; the measured electrical (I-V) diode characteristic curve is obtained at different temperatures 20, 25, 30 and 35°C as shown in "Fig. 5". The measured electrical (I-V) diode characteristic curve shows that the laser diode module is a temperature independent which means that the unit is electrically stable by having a liner relation between the diode laser current and voltage.

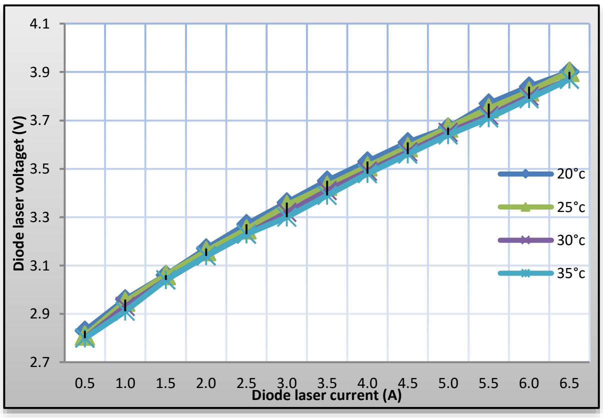

Figure 5. The (I-V) characteristic curve at different temperatures

Also an electrical power characteristic curve is obtained by operating different currents at different temperatures shows that the electrical output power is a temperature independent which means that the unit is also electrically stable by having a liner relation between the diode laser current and the electrical power as shown in "Fig. 6".

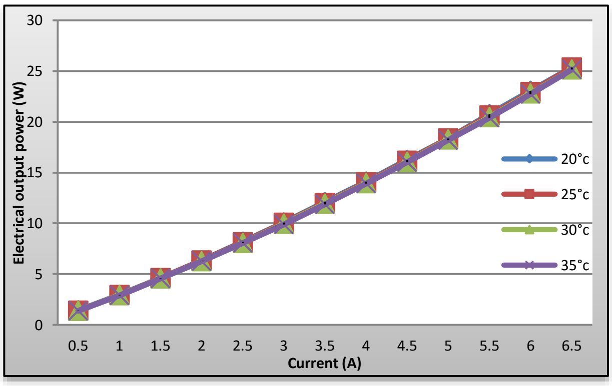

Figure 6. Electrical characteristics curve at different temperatures.

The electrical output power of semiconductor diode laser was measured as a function of the driver input current (I); which is temperature independent. The turning point at which the laser output abruptly starts to increase corresponds to the threshold lasing point. The threshold current (I^{th}) or equivalently threshold current density (J^{th}) is an important device parameter and its minimization is desirable. It is well known that when the input current $I < I^{th}$; light output mainly consists of spontaneous emission only.

B. Optical Characterization of the High power Diode Laser Module

1) Experimental setup

An optical power meter system model (PM100D, Thorlabs) and an integrating sphere photodiode high power sensor model (S142C, Thorlabs) for detection of light signals from 350 to 1100 nm range are used to measure an optical power ranging from 50nW - 500mW as shown in "Fig. 7".

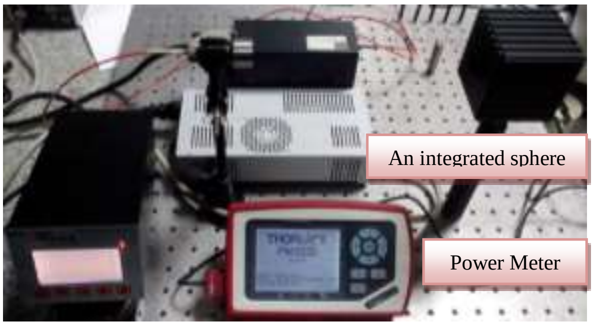

Figure 7. Photograph of the experimental setup

2) Optical Measurements Results

The output optical laser power at different operating temperatures is measured using the optical power meter and the integrating sphere photodiode high power sensor; corresponding to the change in the driving input current to the diode laser module. We have measured the diode output laser power in (Watt) versus the diode input driving current in (Ampere) at different temperatures of 20, 25, 30 and 35 °C. The optical power characteristic curve was plotted at different temperatures showing the temperature effect on the threshold lasing point and the linear relation between the output optical laser power and the input driving current behind threshold point, as the laser operated continuously without any indication of heating or failure and the results illustrate that the laser threshold output is slightly increasing with the temperature. The Optical characteristics curve of the high power diode module at different of operating temperatures was investigated to determine the highest power of 1.88 W that can be achieved at a certain temperature of 35°c and a driving current of 6.5 A as shown in "Fig. 8".

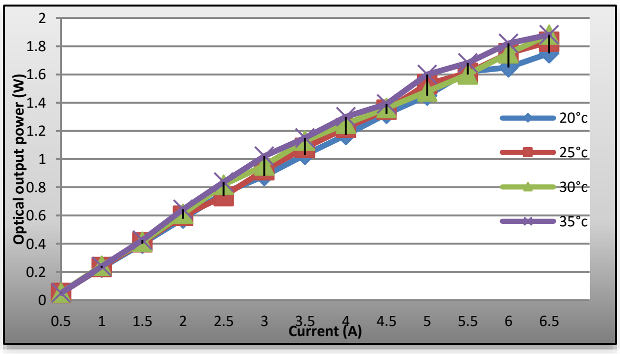

Figure 8. The optical characteristics curve at different operating temperatures.

The conversion efficiency of the diode laser was found by plotting the output optical power from the pigtail fiber coupled diode module and the electrical power at different driving currents and different temperature as shown in "Fig. 9".

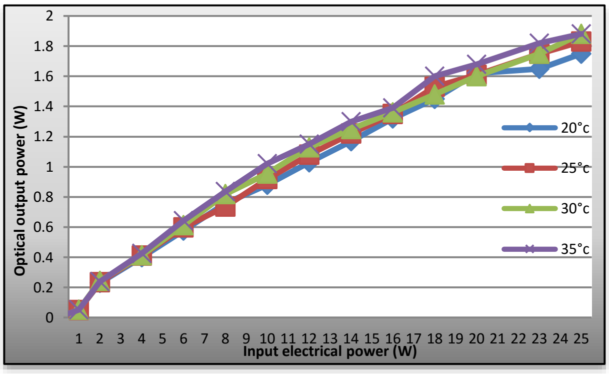

Figure 9. The Optical characteristics (L-I) curve of the high power diode module

From the measurements shown in “Fig. 8” and “Fig. 8”, the maximum slope efficiency is around 25% at a wavelength of 980 nm. The decreasing in the measured slope efficiency with increasing pumping current shown in “Fig. 10” occurs because of the Ohmic losses in the diode laser increasing with the square of the current; where the output electrical power is in linear relation with the driving current as shown in “Fig. 5”.

From these experimental results; it is clear that at temperature of 35°C, the (L-I) curve has the highest threshold value with the lowest conversion electrical to optical slope efficiency in this case.

From the temperature effect on both of threshold lasing and the conversion slope efficiency; taking into account the measuring results of the electrical characterization shown in “Fig. 5”. The operation of the high power diode laser module at temperature of 35°C was the best condition, it gave the higher slope efficiency with lower consumption of electrical power and lower threshold lasing which considered to be an optimum condition producing a maximum output performance at temperature of 35°C as shown in “Fig. 10”.

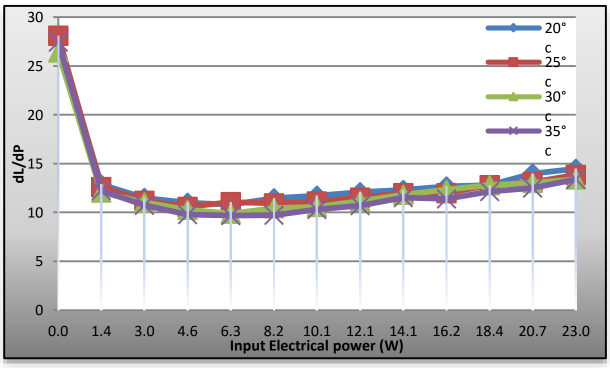

Figure 10. Different slope efficiencies at different temperatures.

C. *Temperature effects on the wavelength measurements in CW laser mode*

1) *Experimental setup*

A high resolution spectrometer model (NIRQUEST) that covers the wavelength range from 900-2500 nm, fiber optic cable, collimated optics, high power pigtail diode laser module and “Spectra Suite” computer software are used to measure the wavelength as shown in “Fig. 11”.

Figure 11. Photograph of the experimental setup

2) *Optical Measurements Results*

The spectrum of the high power diode laser module for different driving currents from 0.5A to 7A at different temperatures from 25 °C to 35 °C controlled by the laser diode driver is measured, recorded and investigated, the result is typically as shown in “Fig. 12(a-d)”.

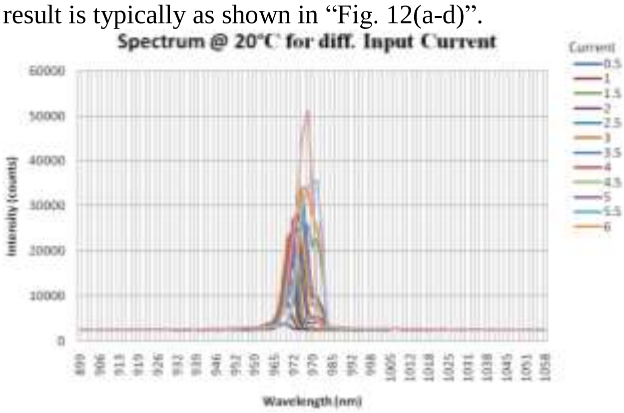

Figure 12. (a) The measured wavelength at 20°C

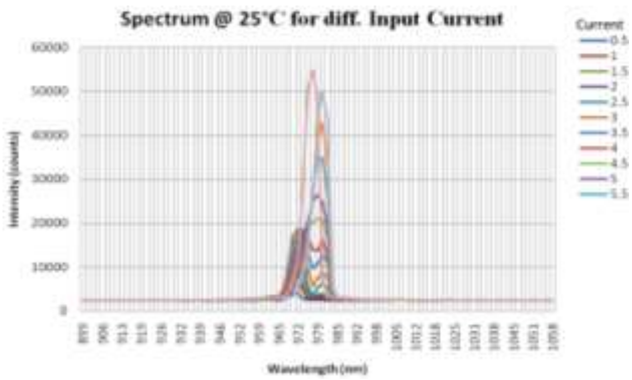

Figure 12. (b) The measured wavelength at 25°C

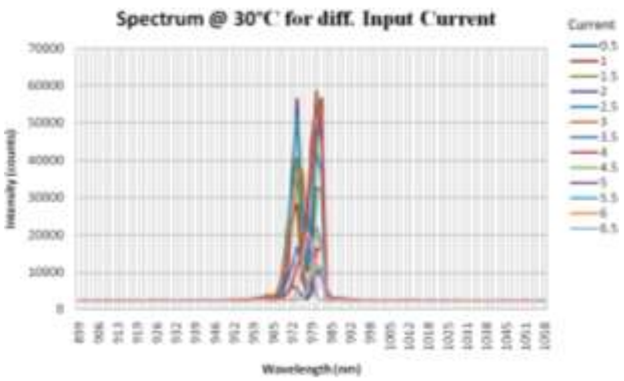

Figure 12. (c) The measured wavelength at 30°C

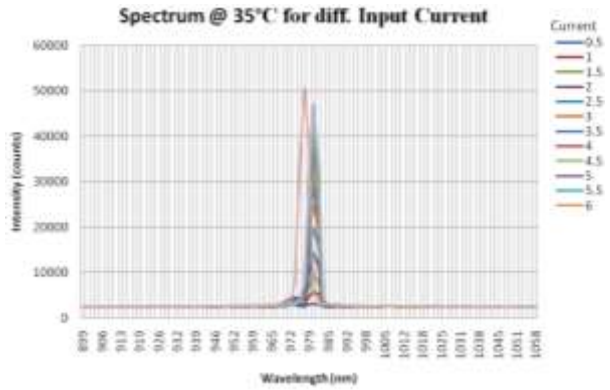

Figure 12. (d) The measured wavelength at 35°C

Figure 12. The spectrum of the 980 nm high power diode laser with different currents operating at different temperatures (a) 20°C, (b)25°C, (c)30°C, (d)35°C.

From the above experiments and measurements that are illustrated in "Fig. 12", it was noticed that the wavelength will slightly change; doubled mode with respect to the temperature variation in the output wavelength at 980.34 nm which mean that the emitted laser wavelength is affected by the temperature increasing and being shifted by the current increment. This experiment was maintained to investigate the stability of the unit used. It can be observed that the best operating temperature for the diode laser with respect to wavelength 980 nm is at temperature of 35°C because it's one mode without any shift for all the driving current from 0.5A to 6.5A; although it was being shifted from the central wavelength 980 nm at the current of 7A.

D. *The beam profile of the high power diode laser module*

The TEM00 laser mode with a high efficiency, high output power, good spatial beam profile and good stability is highly desired in the quad detector tracking system so a thermal camera is used to capture the thermal image showing the optical output Gaussian shape at a distance of 7 m from the high power diode laser module.

1) *Experimental setup*

A high power diode laser fiber coupled module model (VDM00231) operating at 980 ± 2 nm, an integrated highly precise temperature controller model (UM series DiTec, Jenoptik), power supply (output 24V, 10.5A), a fiber cable as shown in "Fig. 7"; and a thermal camera model (Ti20, Fluke Thermal Imager) are used to investigate a beam profile.

2) *Optical Measurements Results*

A thermal image of a laser beam at a stabilized wavelength of 980 nm is produced by using the thermal camera on a target at a distance of 7 m away from a the laser source, this thermal image has the shape of a Gaussian beam profile as shown in "Fig. 13".

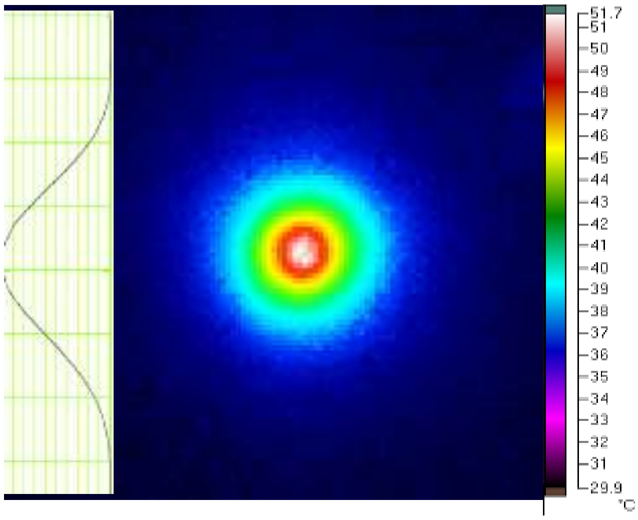

Figure 13. Output thermal image of diode laser module with a stabilized wavelength at 980 nm.

E. *Laser modulation with different pulse repetition frequencies (PRF)*

Laser designators and seekers use a pulse coding system to ensure that a specific seeker and designator combination work in harmony. By setting the same code in both the designator and the seeker, the seeker will track only the target illuminated by the designator. The pulse coding used by all systems is based on Pulse Repetition Frequency (PRF). Coding allows simultaneous or nearly simultaneous attacks on multiple targets by a single aircraft, or flights of aircraft, dropping Laser Guided Weapon (LGW) set on different codes. This tactic may be employed when several high-priority targets need to be attacked expeditiously and can be designated simultaneously by the supported unit(s). This controlled code assignment prevents interference among joint force unit activities. Each component's supporting arm divides its codes among its subordinate units. Subordinate units assign codes to individual missions and change codes periodically, as the situation requires. At each step of this process, laser codes must be allocated to ensure compatibility between laser designation equipment and munitions. Some munitions and equipment are incapable of using all codes. Additionally, certain codes (low code, high PRF, and/or faster pulse rate) are preferred for laser systems requiring precision guidance, Laser codes are normally simple PRFs in the 10 to 20 Hertz rage[5]

1) Experimental setup to investigate the pulse to pulse stability

A signal generator model (33500B series, Agilent Tec.) which is connected externally to a controller to pulsate the diode laser, photo detector model (DET10C, THORLABS) which is a biased Indium Gallium Arsenide (InGaAs) detector designed and an oscilloscope model (DSO-X 3052A, Agilent Tec) are used to investigate the pulse to pulse stability as shown in “Fig. 14”.

Figure 14. Photograph of the experimental setup

2) Measurements procedures and Results

By using the main experimental setup, the responsivity of the output diode laser using different frequencies 5, 10, 15, 20, 25 Hz (the most frequencies used in the military applications) can be investigated by monitoring the laser output on the oscilloscope as shown in “Fig. 15(a-e)”.

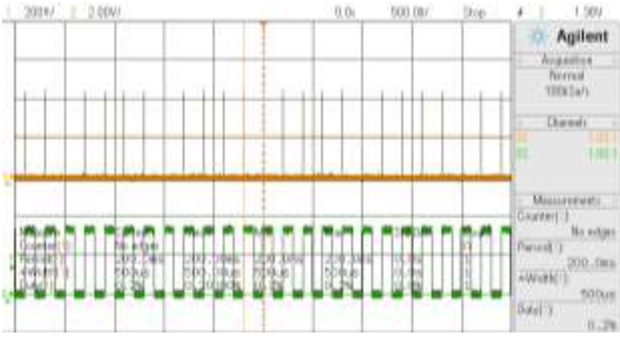

Figure 15. (a) A The pulse to pulse stability at 5Hz

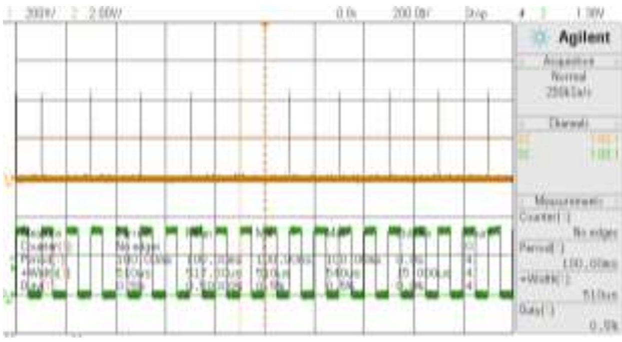

Figure 14. (b) The pulse to pulse stability at 10Hz

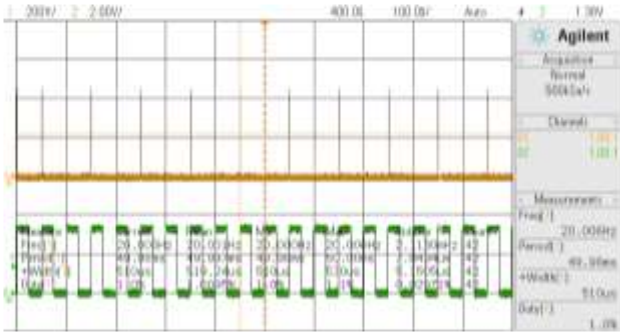

Figure 14. (c) The pulse to pulse stability at 15Hz

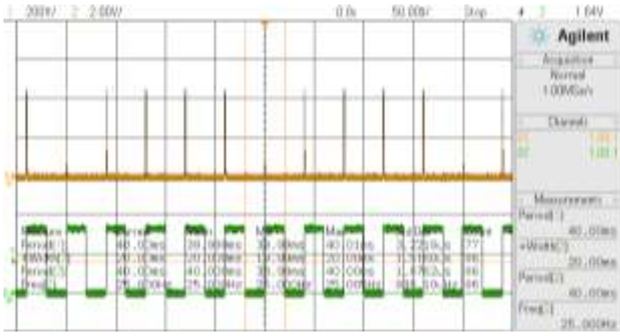

Figure 15. (d) The pulse to pulse stability at 20Hz

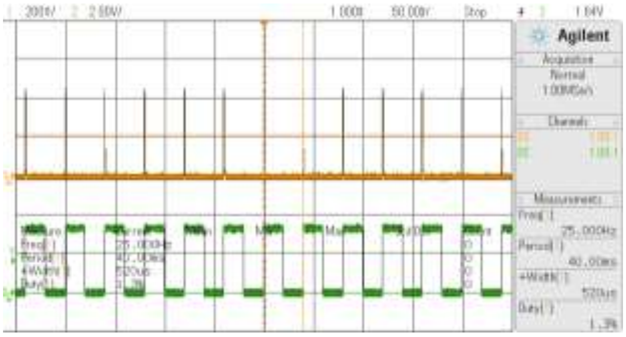

Figure 15. (e) The pulse to pulse stability at 25Hz

Figure 15. Laser pulse trace at frequency of (a) 5Hz, (b) 10Hz, (c) 15Hz, (d) 20Hz, (e) 25Hz.

The responsivity of the output diode laser versus different frequencies has been investigated, it was found that it has a high pulse to pulse stability more than 90% at all frequencies ranges from 5Hz to 25Hz like a clearly pulse trace at a frequency of 10Hz as shown in “Fig. 16”.

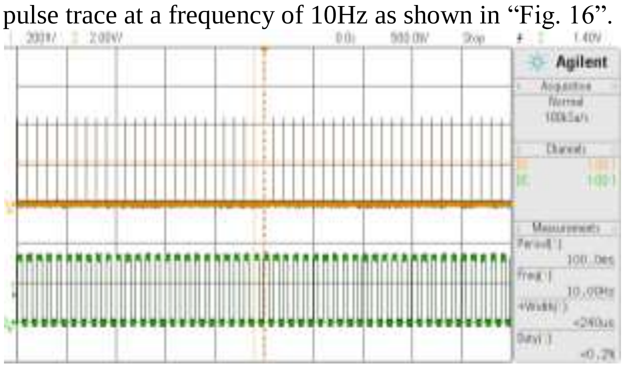

Figure 16. Laser pulse trace at frequency of 10Hz

3) Experimental setup to investigate the wavelength stability at pulsed mode of operation

A high resolution spectrometer model (NIRQUEST), fiber optic cable, collimated optics and computer software “Spectra Suite” shown in “Fig. 11” with the test System experimental main setup shown in “Fig. 16” are used to investigate the wavelength stability.

4) Measurements procedures and Results

The wavelength stability has been investigated by using a high resolution spectrometer while adjusting the signal generator to different frequencies 5, 10, 15, 20, 25 Hz (the most frequencies used in the military applications) at different temperatures then measuring and recording the result using the “Spectra Suite” computer software as given in the Table II.

TABLE II. RECORDED RESULTS OF WAVELENGTH

	Temperature (°C)			
	20	25	30	35
Frequency (Hz)	Wavelength(nm)			
5	970.44	973.74	981.99	973.74
10	970.44	975.39	975.39	981.99
15	970.44	973.74	975.39	981.99
20	970.44	973.74	975.39	981.99
25	970.44	973.74	975.39	981.99

The most stable wavelength has been achieved at a certain temperature which is 20°C, the moderate wavelength stability is at temperature 25°C and the lowest wavelength stability is at temperature of 30°C and 35°C (best stability at temperature of 35°C starting from a frequency of 15Hz) as shown in “Fig. 17”.

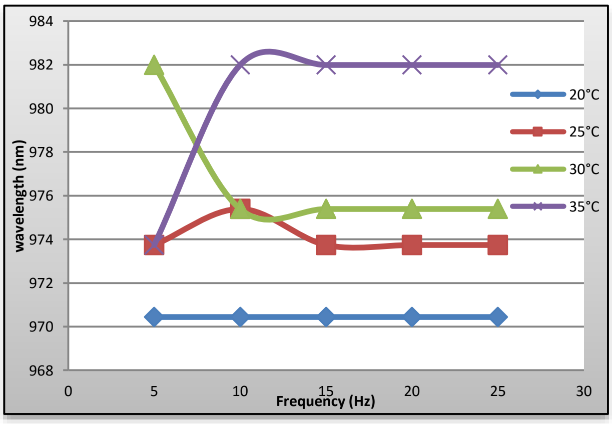

Figure 17. The wavelength stability

F. Conclusion

Experimental studies on the operation and the optical characteristics curve of the high power diode laser module at different operating temperatures is investigated and characterized to be used at a designation and tracking system in order to determine the highest power of 1.88 W that can be achieved at a certain temperature of 35°C at a driving current of 6.5 A, It gave the higher slope efficiency with lower consumption electrical power and lower threshold lasing. The high power diode laser module operating at wavelength of 980 nm and temperature of 35°C or a wide range of driving current ranges from 0.5A to 6.5A. The laser pulse to pulse stability of more than 90% is investigated at a driving current of 6.5A and the highest power of 1.88 W at all frequencies range from 5Hz to 25Hz.

The highest wavelength stability is determined at a temperature of 20°C and it is stabilized at all frequencies ranged from 5Hz to 25Hz , the lowest wavelength stability is determined at a temperature of 30, 35°C and it is stabilized at frequencies ranged from 15-25Hz. Finally, the optimum performance of the high power diode laser module of 1.88 W operating at wavelength of 980 nm is achieved at temperature of 35°C and frequencies ranges from 15Hz to 25Hz with a high pulse to pulse stability of more than 90%.

IV. DESIGN, SIMULATION AND IMPLEMENTATION OF AN INTELLIGENT LASER TRACKING SYSTEM (LTS)

A. Introduction

One of the main components of the laser tracking system is the optical system for collimating the reflected beam from the target, the Quad Detector (QD) which is simply consists of four photodiodes capable of detecting light spot projected on its surfaces and determine the deviation position of the laser spot from its center then converts the incident laser spot to its corresponding photocurrent, the readout circuit that filter and convert the photocurrent to its corresponding voltage and the tracking system that is controlling the laser seeker movement to track the intended target based on the feedback information of the QD depending on the real position of the tracking platform.

In this chapter, the design, simulation and implementation of an intelligent laser tracking system (LTS) is described in details. It involves three major areas:

- Design and simulation of an electrical interfacing read out circuitry of QD.
- Design and construction of the Laser optical seeker system.
- Design and implementation of the fuzzy logic control software and hardware.

Each area had its own unique problems and considerations.

B. Design and simulation of an electrical interfacing read out circuit of QD

1) QD photodiode principle of operation and structure

The QD photodiode unit consists of 4 separate P on N silicon photosensitive surfaces separated by a small gap. A P-Type Quad Silicon Detector (product data sheet for Model SD 551-23-41-221) is experimentally used in this work as shown in “Fig. 18”. The detector is a (Near Infrared) NIR enhanced silicon P-type detector used for application requiring fast response with low capacitance and high responsivity packaged in a hermetic TO-8 metal package. In this QD unit, the effective active area diameter is 13.97mm, the viewing angle is 43° and the gap is 0.25 mm. It has required specific features like low capacitance, high speed and high responsivity that can be used in laser guided munitions. It has 7 electrical pins which consist of four cathode (A, B, C and D) pins, a one common anode pin, a grounded case pin and a guard ring pin. The laser beam is usually pointed towards the dead center between the 4 quadrants and the beam diameter is selected to fit inside of the total quadrant area (typically half of QD diameter)[6] that the light spot has to overlap all segments at all times and it cannot be smaller than the gap between the segments. It is important to have a uniform intensity distribution of the light spot for correct measurements. They are excellent devices for applications like nulling and beam centering.

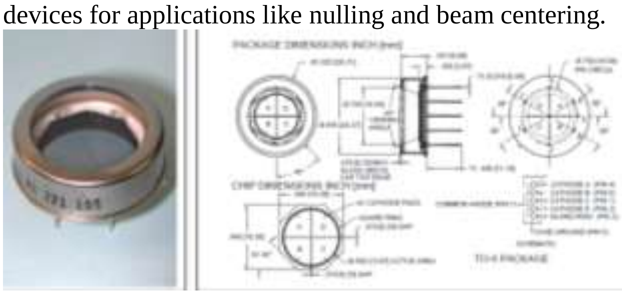

Figure 18. A P-Type Quad Silicon Detector

Although light falls on all four quadrants, the difference between the left and right quadrants (X output) and top and bottom quadrants (Y output) can be adjusted to zero by centering the beam, whereas the SUM is at a maximum. The device X and Y output voltages thereby become very sensitive to slight deviations in the position of the beam from this initial centered setting. The SUM value on the other hand can be used to measure changes in the beam intensity, so this can be used to correct the X and Y output values for voltage changes that are due to intensity fluctuations rather than actual beam deviations[7].

A quadrant detector works by producing an electrical signal in each quadrant “A, B, C, or D, as depicted in “Fig. 19(a-c)” that is proportional to the intensity of the light that impinges on each quadrant.

There are two ways used to process these signals which are:

- The “bang-bang” method compares opposite quadrants or directions and the spot is dithered around the null position as the comparators make a series of corrections. A typical “bang-bang” system is described in[8].
- A second more complex method, which is used in this thesis, measures the peak amplitudes of the signal in each of the four channels. If the four quadrants are A, B, C and D, then one axis is (A+B)-(C+D) and the other axis is (A+D)-(B+C). Dividing by the sum channel, (A+B+C+D), may normalize these signals. This approach may give a proportional area to optimize the response of the tracking elevation and azimuth servos [9]. A symmetrical optical beam generates equal photocurrents in all segments, if positioned at the center. The relative position is obtained by simply measuring the output current of each segment. They offer position resolution better than 0.1 μm

The center on a quadrant photodiode is given by equations 1 and 2:

$$X = \frac{(A+D)-(B+C)}{A+B+C+D} \qquad (1)$$

$$Y = \frac{(A+B)-(C+D)}{A+B+C+D} \qquad (2)$$

Where:

X and Y represent the position coordinate of the laser spot on the surface of QD.

This information is used to take control decisions about how to align the platform of the LTS with the target. The target is the component which moves in relation to the tracking platform, and which the tracking platform must follow. The objective of the tracking problem is to reduce the difference or the error between the line of sight of a tracking platform (the boresight of the weapon) and the position of an object being tracked (the target line-of-sight, or LOS) in order to align a tracking platform with its target.

This design can also be generally used as a Laser Spot Tracking System (LSTS) to simultaneously process multiple targets with position and code data (after designing an addition circuit to catch only the matched code). Laser spot trackers have been used for many years to steer a weapon system onto target. Typically a pulsed narrow beam laser illuminates the target then the laser light is scattered from the target. The tracker or seeker lens collects the some of the scattered light and condenses it into a spot. The tracker is steered until the spot is divided equally into four equal signals normally using this quad detector the null position. In this position the tracking head boresight is pointed at the target [10].

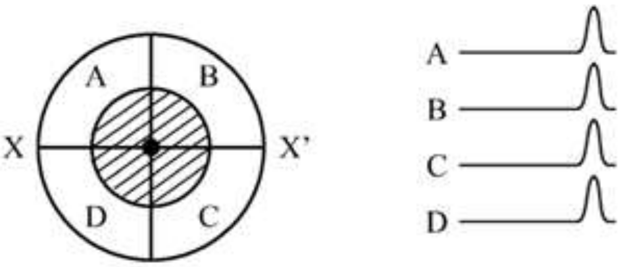

Figure 19. (a) Centered laser spot with four equal signals on QD

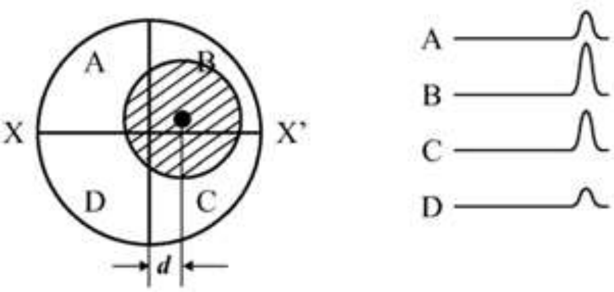

Figure 19. (b) Shifted laser spot with distance "d" with different signals on QD

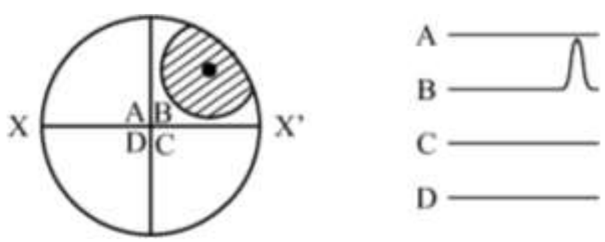

Figure 19. Fig. (c) laser spot incident in quadrant "B" on QD and its signals

Figure 19. Laser spot incident in different quadrants of QD

These detectors have the ability to measure extremely small changes in the position of a light beam and are used for centering, nulling and detecting and measuring position displacements.

2) QD Read out circuit and its simulation

In order to present the outputs of the 4 quadrants as X, Y and SUM, it is necessary to first amplify the individual quadrant outputs, and then combine them using a series of sum and difference amplifiers (for X and Y) or just a sum amplifier (for the SUM output) so it consists of a preamplifier stage, a post amplifier, a reciprocal amplifier, and an analog to digital converter as shown in "Fig. 20".

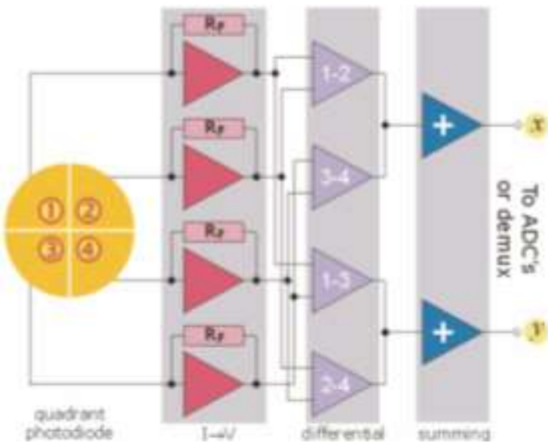

Figure 20. The general block diagram of the four quadrant detector with processing circuit for laser position determination

The output current of the quadrant photodiode detector (order of µA) is fed to a trans-impedance amplifier (preamplifier stage) to get output voltage that is proportional to the incident laser power on the surface of each quadrant that used in tracking system.

In this work, an intelligent algorithm will be used to enhance laser detection system (LDS) by using an Arduino Due microcontroller to implement the function of the 2nd and 3rd stages of the block diagram, this method has been designed and simulated by using a computer added design (CAD) software "Proteus 8 Professional".
The 1st stage of the block diagram shown in "Fig. 20" that converts the photocurrents to its corresponding voltages has been designed using the electronic components simulated using "Proteus 8 Professional" as shown in "Fig. 21", then the output four analog signals of this 1st stage are connected to four analog input pins of a microcontroller to do the differential and summation stages (2nd and 3rd stages the block diagram shown in "Fig. 20"), the output of the microcontroller has been monitored in a digital monitor on the program indicating the four QD values and the two positions in X and Y (Serial monitor of the microcontroller).

A wide-dynamic range optical receiver amplifier is provided by using two separate amplifiers. The amplifier is a low-impedance input, low-noise, high-gain amplifier, preferably a transresistance low power, quad operational amplifier (LM324). A trans-impedance amplifier differs from a normal inverting (gain) amplifier in that an input resistor is not needed for the amplifier, since the photodetector already has a very high internal resistance which serves as the input resistance for the amplifier.

A simulated light-induced signal source is connected to the input resistor such that signal current from the simulated light-induced signal source flows through the input resistor into the amplifier input. This amplifier is considered to be the most critical part. The integrating circuit has been used, which transforms current pulse into a voltage pulse with an amplitude proportional to a charge carried by the current pulse. In general, the function of a preamplifier is to amplify a low-level signal to a line-level. The preamplifier provides voltage gain (e.g. from 10 millivolts to 1 volt).

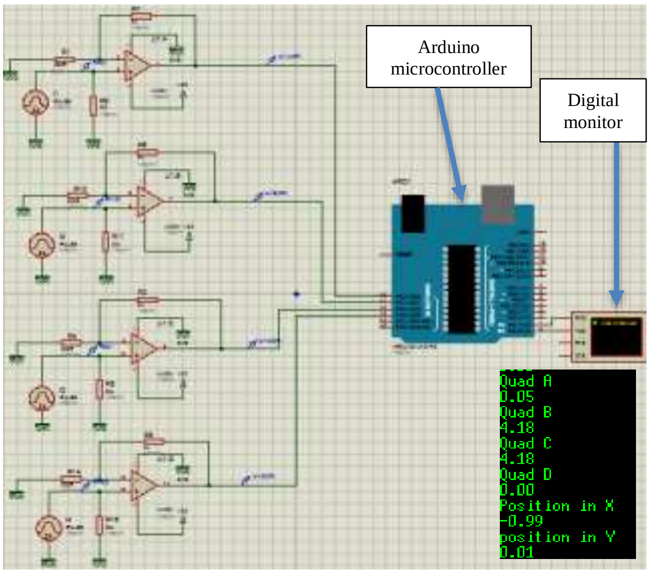

Figure 21. The simulation of the Quad detector signal processing

To obtain an adequate signal from the trans-impedance amplifier; First, the gain of the trans-impedance amplifier required an extremely large feedback resistance, in the order of mega ohms, to provide a recognizable signal. This gain was needed to provide signals large enough to combine in the next steps of Arduino microcontroller.

From the circuit shown in “Fig. 21”, we can determine the gain of the circuit by the equation 3:

$$\frac{V_o}{V_i} = G = \left(1 + \frac{R_2}{R_1}\right) \qquad 3$$

Where:

G is the gain

V_o is the output voltage

V_i is the input voltage

3) Implementation of QD read out circuit

In order to implement the read out circuit described in the previous section, a bread board is used with trans-impedance amplifier (LM324) which is low-power quad-operational amplifier directly connected to the output of the QD as shown in “Fig. 22”.

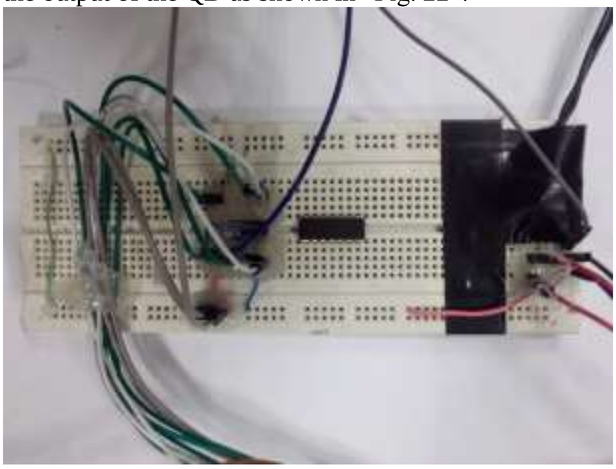

Figure 22. Implementation of the readout circuit on a breadboard

C. Design and Construction of the laser optical seeker system

1) Theory of operation and Components of an laser optical seeker system

The optical sensor design and selection is paramount to meeting the requirements of the proposed seeker system’s mission. The focal plane must be able to acquire a target signal and, based on the incoming signal, translate the error in the estimated position to the missile control system for flight corrections. This action requires fast sensor response times due to the short time window allowed in the seeker controlled portion of flight, as well as adequate performance to distinguish the desired designator signal from the detector from the background noise present.

Laser energy reflected from the target enters the front, or dome optics, of the weapon system. The dome optics includes a band-pass filter to block energy outside the 1.06 µm laser wavelength. The high contrast image of the laser spot is defocused onto a photodetector assembly, mounted directly behind the dome as shown in “Fig. 23”.The photodetector is usually a quad cell detector, which is a photodiode whose active area is partitioned into four discrete quadrants[11].

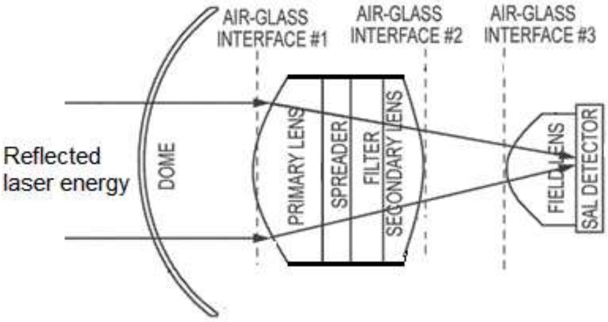

Figure 23. A typical optical laser seeker system

The defocused spot is projected onto the four quadrants to allow currents to flow. These currents can be taken as a measure of how much energy in the defocused spot lies on each specific detector. The electrical signal at the output of each of four sensitive areas of the photo receiver depends on the value of radiant flux falling onto the corresponding area, so to form the position characteristic, it is necessary that the image of laser spot covers all four areas of the photo receiver as the spot moves within the given field of view. The laser light reflected from the target comes to the input of the optical systems of the seeker and is separated from the sun background of the underlying surface by the narrow band interference filter. On the surface of the photo receiver the single lens forms a light spot with a diameter (d_3) about half the diameter (d_2) of the photo receiver as shown in “Fig. 23”. The voltage of the signals picked off the photo receiver areas is proportional to the energy of the light pulse reflected from a target as well as to the area of light spot falling onto an appropriate area[12].

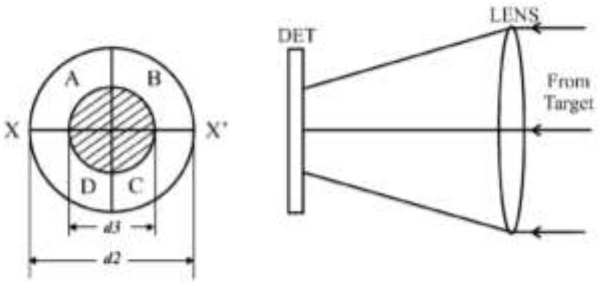

Figure 24. light rays from the target being defocused by a lens on the QD

Figure 26. Front and rear view of the laser tracking system

D. Design and construction of the tracking platform

In this work, the tracking platform was built as a heavy duty pan/tilt bracket that consists of two brackets and all the hardware that was needed to attach them to make a pan/tilt mechanism using two servo motors as shown in “Fig. 25”.

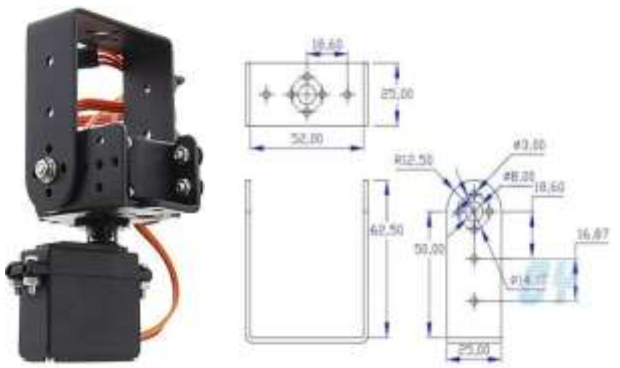

Figure 25. A heavy duty pan/tilt bracket design with two servo motors

This pan/tilt has the long arm kit for increased travel and motion on the tilt axis but decreased load ability. It is made from powdered coated metal for rigidity and has a ball bearing support. It works with standard size servo (15, 12, 7.5, 3.2 kg.cm)[13]. It was selected for use in construction of the tracking platform because it is easy to machine and because it acts as a natural QD lubricant, which was useful in reducing the friction of the system.

This two-dimensional optical tracking platform has been used to hold the optical system (quadrant detector sensor, the lens, the plastic casing and the wires) as shown in “Fig. 26” and make the system flexible to move in both azimuth and elevation directions. The breadboard, the electronic components and the Arduino micro controller are connected to this tracking platform with long wires to not affect its movements in the both directions (Azimuth and Elevation).

Two types of data were obtained from the system optics for each of the two axes (azimuth and elevation): position and rate of change of the position (derivative or velocity) of the laser image with respect to the tracking platform. The specific objective of this application was to center the image of the target laser in the optics of the tracking platform using fuzzy logic controller as the control for the tracking device. It was chosen two dual ball bearing servo motors with a plastic gearbox for this application.

The characteristics of this optical system of the laser spot position determination and the servo motors technical data are mentioned in Table III. The type of lens is a Biconvex glass lens with a diameter of 40 mm and focal lens of +50 mm made in the form of positive meniscus, the plane of the sensitive area of the photo receiver QD is being at the distance of 80 mm from the lens which is more than the focal lens . In this case the scattering spot shape is a circle of 8.5 mm in diameter compared with QD diameter of 16.38 mm (light spot with a diameter about half the diameter of that of the photo receiver) typically as shown in “Fig 25”; it practically does not change in size when a target moves over the field of view of the system.

This allows obtaining a practically linear position characteristic through-out the field of view. This optical system is supported in a black light plastic cylinder with a hole in the back to get the wiring connection from the QD to the Arduino Due microcontroller. This wiring connection is protected by a small plastic cylinder supported in the back of the QD in order to not beak the sensitive 7 pins of the QD.

TABLE III. THE TECHNICAL DATA OF THE LASER TRACKING PLATFORM

Characteristics of an optical system	
Field of view	40 degree
Operating wavelength λ_0	980 nm
Quad detector diameter D	16.38 mm
Total length between QD and lens	80 mm
The servo motor technical data	

Dimensions	39.55mm / 1.5" x 39.55mm / 1.5" x 19.5mm / 0.7"
Torque	90.26 Oz*in / 6.5 kg*cm
Speed	0.21 sec/60°
Weight	46 grams

E. Design and construction of the fuzzy logic control hardware and software

1) Introduction to fuzzy logic controller (FLC)

Fuzzy logic is a branch of artificial intelligence that deals with approximate reasoning algorithms used to emulate human thinking and decision making in machines. These algorithms are used in applications where process data cannot be represented in binary form. So it’s a way of mathematically analyzing the uncertainty of information; it’s a way of dealing with information that is "gray" in nature [14].

Four decades of fuzzy logic oriented activities have revealed that fuzzy logic based systems have the potential for applications in various areas, leading to industrial investment in developing fuzzy logic based products. For example, it is reported that the simulation results of a developed fuzzy model for a nonlinear dc servomotor control showed that it could significantly reduce the effect of the nonlinearities of the dc servo motor which presented a significant improvement in reducing noise effects on the tracking error when used in Laser tracking systems [14, 15].

Fuzzy logic provides a practical, inexpensive solution for controlling complex or ill-defined systems. Despite its contradictory-sounding name, fuzzy logic offers a rigorous framework for solving many types of control problems. Rule-based fuzzy controllers require less code and memory and don’t need heavy number-crunching or complex mathematical models to operate. All that is needed is a practical understanding of the overall system behavior. Fuzzy logic requires knowledge which is provided by a person who knows the process or machine (the expert).

For example, the statements “the air feels cool” and “he is young” are not discrete statements. They do not provide concrete data about the air temperature or the person’s age (i.e., the air is at 65°F or the boy is 12 years old). Fuzzy logic interprets vague statements like these so that they make logical sense. In the case of the cool air, a PLC with fuzzy logic capabilities would interpret both the level of coolness and its relationship to warmth to ascertain that “cool” means somewhere between hot and cold. In straight binary logic, hot would be one discrete value (e.g., logic 1) and cold would be the other (e.g., logic 0), leaving no value to represent a cool temperature. In contrast to binary logic, fuzzy logic can be thought of as gray logic, which creates a way to express in-between data values. Fuzzy logic associates a grade, or level, with a data range, giving it a value of 1 at its maximum and 0 at its minimum.

The input to the fuzzy system is the output of the process as shown in “Fig. 27”, which is entered into the system via input interfaces. For example, in a temperature control application, the input data would be entered using an analog input module. This input information would then go through the fuzzy logic process, where the processor would analyze a database to obtain an output. Fuzzy processing involves the execution of IF...THEN rules, which are based on the input conditions. An input’s grade specifies how well it fits into a particular graphic set (e.g., too little, normal, too much).

Figure 27. Fuzzy logic control system

2) FLC components

Fuzzy logic has rapidly become one of the most successful of today's technologies for developing sophisticated control systems. The three main actions performed by a fuzzy logic controller are (Fuzzification, Fuzzy processing and Defuzzification).

As shown in “Fig. 28”, when the fuzzy controller receives the input data, it translates it into a fuzzy form. This process is called fuzzification. The controller then performs fuzzy processing, which involves the evaluation of the input information according to IF…THEN rules created by the user during the fuzzy control system’s programming and design stages. Once the fuzzy controller finishes the rule-processing stage and arrives at an outcome conclusion, it begins the defuzzification process. In this final step, the fuzzy controller converts the output conclusions into “real” output data (e.g., analog counts) and sends this data to the process via an output module interface. If the fuzzy logic controller is located in the PLC rack and does not have a direct or built-in I/O interface with the process, then it will send the defuzzification output to the PLC memory location that maps the process’s output interface module[16].

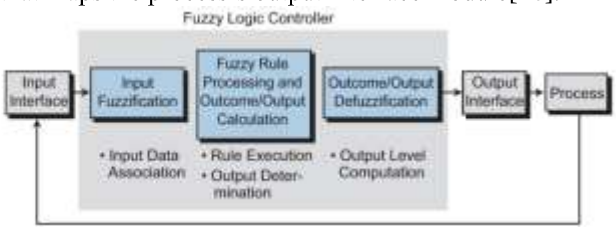

Figure 28. The basic structure of the fuzzy logic controller

3) Design of fuzzy laser tracking controller

Using (MATLAB/SIMULINK) simulation, the laser tracking system for this thesis was designed, simulated and controlled by a simplified version of a fuzzy proportional-integrate-derivative (PID) controller. This control derived its name from the fact that the total control actuation was the sum of the three parts. These parts were based on the error derived from the difference between the desired input and the actual measured output

feedback. The proportional part was a component that is directly proportional to the error, and the integral and derivative parts were proportional to the integral and derivative of the error, respectively. The error was pointed out as the digital signal that converted from the analog output of the QD, which represented the offset of the laser spot from the control point. This error signal also represented the displacement in the laser optical seeker by the target moving which is being illuminated by laser designator. Error change equals the previous error minus the error from the last sampling. To control the laser optical seeker tracking platform as precisely as possible, in this thesis we needed to use different fuzzy sets for each variable: error, change in error and control output. In traditional set theory, membership of an object belonging to a set can be one of the two values: 0 or 1. The FLC was based on the controller's response. To establish the structure of the FLC, the Gaussian shapes of membership function were used. It was supposed that the error is "zero" in an imprecise way. If the error was zero and the change in error was small negative, then the control output was small positive. If the error was small negative and the error change was small negative, then the control output was small negative. Thus, if the error was actually 0.1, its membership in Z would be 0.5, and the value of the Gaussian function was at that point. These rules were reasonable and straightforward so that it was like human reasoning.

In this thesis, all the IF-THEN rules are collected together and formed a lookup table for the fuzzy controller that was much more concise and easier to manipulate as shown in Table IV. The proposed system has a set of linguistic variables to represent the output control signal, five Gaussian MFs, one S-shape MF and one Z-shape MF as shown in "Fig. 29". These MFs were defined as: negative big (NB), negative medium (NM), negative small (NS), zero (ZR), positive small (PS), positive medium (PM), and positive big (PB). The fuzzy set, or membership functions, and control rule were combined together to form the lookup table, and the outcome of the step was a fuzzy variable. The output could be obtained from the lookup table directly, and the outcome of the step was a crisp variable again. The method was used to obtain the lookup table and was to use the input error and change in error, combined with the membership function, to calculate the output in real time. This method was accurate and smooth for the control output.

For a rule base to be valid, it must incorporate information about every possible condition that the system can be expected to encounter. Each unique combination of conditions will correspond to a control decision in the form of a rule. In this tracking problem, two variables are considered for each axis with each variable breaking its domain into seven input membership functions, or conditions. Thus a total of 25 rules were constructed for the vertical tracking axis control as shown in Table IV, these rules were formulated one by one, and then the whole rules set were analyzed to make it:

- Complete: if any combination of the inputs fired at least one rule.
- Consistent: if it does not contain any contradictions.
- Continuous: if it does not have neighboring rules with output fuzzy sets that have an empty intersection.

Once the lookup table was constructed, no further modification of its structure or entries was ever attempted. The model of the motor and its drive system was actually identified by using MATLAB Identification Toolbox.

TABLE IV. THE PROPOSED SYSTEM RULE BASE

Error \ Rate	PB	PS	ZR	NS	NB
PB	PM	PM	PM	PB	PB
PS	PS	PS	PS	PM	PM
ZR	NS	NS	ZR	PS	PS
NS	NB	NM	NS	NS	NS
NB	NB	NB	NM	NM	NM

The proposed system shown in "Fig. 30" has two inputs; the detector deviation signal and the rate of the error signal and one output signal (PWM) to control the motors. It uses Mamdani fuzzy system with five membership functions (five-label) fuzzy sets for the two inputs (Rate - Deviation) and seven membership functions fuzzy sets for the output (Movement) as shown in "Fig. 29(a-c)" and "Fig. 30".

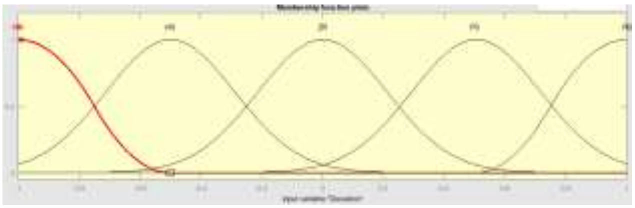

Figure 29. (a) The 1st input variable "Deviation"

Figure 29. (b) The 2st input variable "Rate"

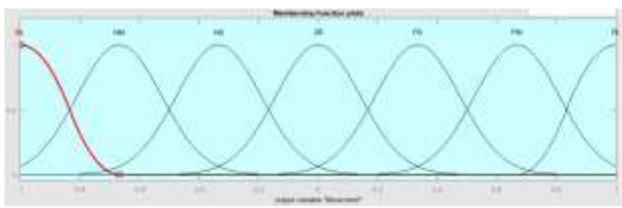

Figure 30. (c) The output Membership function "Motor Movement"

Figure 29. The proposed Mamdani fuzzy system membership functions

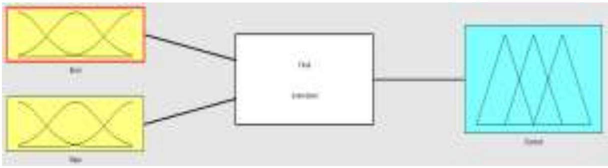

Figure 30. Mamdani fuzzy system

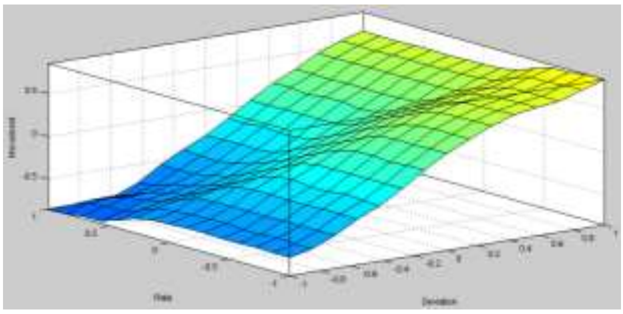

Figure 31. Fig. The 3D proposed system control surface

It was found using (MATLAB/SIMULINK) simulation that using the Z, S functions, at the ends of membership functions (MFs) and Gaussian shaped membership functions at the rest of MFs yielded smoother tracking performance and faster time responses than FLCs that used either triangular or trapezoidal membership functions.

In this work, an algorithm of the microcontroller uses the fuzzy logic to improve the controlling process and so improving the tracking performance of the two servo motors which are used in the tracking platform, this is happened by moving the QD with the laser beam reflected from the target and makes the laser spot incident on its surface always be in its centroid position. In other words, the output of the microcontroller has been processed by the proposed fuzzy system to control servo motors to center the spot position on the quad detector. The most important things in fuzzy logic control system designs are the process design of membership functions for inputs, outputs and the process design of fuzzy if-then rule knowledge base.

It is useful at this point to explain the similarities and differences between fuzzy logic control and artificial intelligence. Both artificial intelligence and fuzzy logic control use a set of IF-THEN rules which describe what action is to be taken if a certain set of conditions is met. Artificial intelligence rule bases, however, have a finite number of control points - one control point for every IF-THEN rule. In a fuzzy rule base, there are still a limited number of IF-THEN rules, but an infinite number of control points are possible because a fuzzy rule base maps membership values to corresponding control values. This means that a fuzzy rule base recognizes information that is fuzzy or partially true in nature, and can partially "fire" or invoke more than one rule at any one time. It is useful to demonstrate these concepts through an example.

In the tracking problem being considered, it is desired to position the tracking platform so that it is in line with its intended target. If the tracking platform is far out of position with respect to its target, then one could make the rule:

If the error is LARGE, then the control output is LARGE.

This makes sense. If the platform is seriously out of line with the target, then a large control force is needed to move the platform quickly back into position. Likewise, if only a small discrepancy exists between the platform and its target, then one could derive the control rule:

If the error is SMALL, then the control output is SMALL.

This, too, makes sense. If there is only a small inconsistency between the control platform and the target, then only a small correction is needed. Adding directional information, one gives the control outputs further meaning. For instance:

If the error is LARGE POSITIVE, then the control output is LARGE POSITIVE.

If the error is SMALL NEGATIVE, then the control output is SMALL NEGATIVE.

These rules simply mean that if the tracking platform is displaced to one side of the center point, then a force is needed in the same direction to bring the platform back in line. All of the rules above are valid, but they only incorporate knowledge of one input variable, position, in the control decision. The tracking problem considered, however, includes information about two variables - position and rate of change of position. An example of a rule that takes both variables into account is:

IF the error is LARGE POSITIVE AND if the rate of change of the error is LARGE NEGATIVE, then the control output is LARGE POSITIVE.

If the target is well to one side of the center point of the tracking device, and if the tracking device is already moving quickly in toward the center point, then little, if any, extra effort is needed by the controller to place the tracking platform back on mark.

Fuzzy control should not be employed if the system to be controlled is linear, regardless of the availability of its model. PID control and various other types of linear controllers can effectively solve the control problem with significantly less effort, time, and cost. PID control should be tried first whenever possible [14]. The benefits of fuzzy controllers can be summarized as follows:

- Fuzzy controllers are more robust than PID controllers because they can cover a much wider range of operating conditions than PID, and can operate with noise and disturbances of a different nature.
- Developing a fuzzy controller is cheaper than developing a model-based or other controller to do the same thing.
- Fuzzy controllers are customizable, and it is easier to understand and modify their rule, which not only uses a human operator's strategy, but is also expressed in natural linguistic terms.
- It is easy to learn how fuzzy controllers operate and how to design and apply them to a concrete

application it is also worth noting that fuzzy logic can be blended with conventional control techniques. This means that fuzzy systems do not necessarily replace conventional control methods. In many cases fuzzy systems augment them and simplify their implementation[16] .

4) Simulation

The proposed system is modeled and simulated based on PID like fuzzy logic controller using MATLAB/SIMULINK program. This is done by applying a same input (unit step function) to two identical servo motor models as shown in the block diagram of “Fig. 32” according to the following procedures:

- Directly to the 1st servo motor model.
- Through connecting a fuzzy block with a previous input/ output membership functions and the proposed system rules to the 2nd servo model.
- Subtracting the feedback after servo model output (practically, the servo real movement) from the unit step input.
- Monitoring and recording the output using oscilloscope.

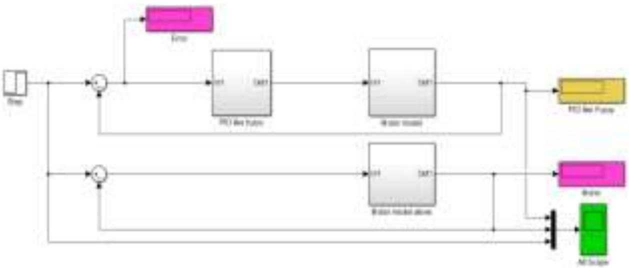

Figure 32. The proposed system block diagram

The simulation result was monitoring and being recorded by an oscilloscope to show a comparison between the output of a servo motor with and without using PID like fuzzy control technique as shown in “Fig. 33”.

Finally, it was proven that the fuzzy logic controllers (FLC) can outperform classic controllers in such applications. The advantages of utilizing a proportional–integral–derivative (PID) like fuzzy controllers to improve the control performance for a system with noise and a relatively long time delays, no need for the mathematical model of the system as in conventional controller as the knowledge of the moving target dynamics and the statistical uncertainty model are not available. In these situations, the use of expert knowledge is a reasonable alternative and cover a much wider range of operating conditions than PID can and can operate with noise and disturbances of different nature.

That is confirmed by simulation results. The tracking requirement was satisfied without broken point during the tracking process. The output of the system was very smooth and fast.

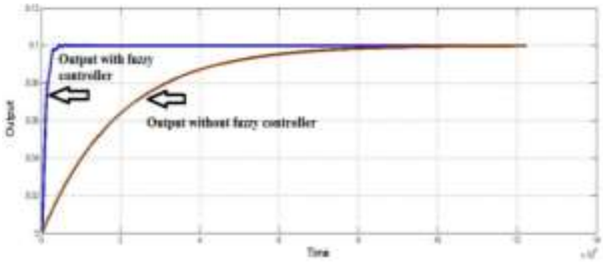

Figure 33. The simulation results

F. *Implementation using Arduino Due microcontroller*

1) Introduction

The Arduino microcontroller is used in art and design as an open source programmable tool to create interactive works. It can drive motors, LEDs, sensors and other components. Microcontrollers are small computing systems used for low power and low memory purposes. It consists of a microchip on a circuit board with read-write capabilities, memory, inputs and outputs. The Arduino microcontroller adheres to these capabilities. While microcontrollers have had a presence in the arts for decades, the Arduino microcontroller is among the first microcontrollers specifically designed for artists and designers. The Arduino microcontroller allows artists and designers to execute electronic-incorporated works without knowing the internals of the hardware or software. Artists and designers have been influential in the evolution of the Arduino[17] .

In this work, the Arduino microcontrollers were used as the circuit organizer for the motors and the sensor. The first step that was done in designing the control unit is checking from the industry for the available required products and understanding the types of motors that can be used for controlling the movement of the laser tracking system in both directions (azimuth and elevation), according to some principles such as the LTS seeker’s weight, volume and the movement required. Also it was essential to send a feedback from the sensors to the controller, as an example, the four quadrants of the QD sensor and the motors feedback signals to ensure that the right exact movement was achieved. It was planned for the motion control circuit to use Arduino Duo microcontroller to control the servo motors for LTS. It was designed in a way that uses the pulse width modulation (PWM) technique to give the servo motors the right angle to move.

The Arduino Duo is connected to the output of the QD read out circuit and the two servo motors which will receive their orders to move by the output of digital PWM output pins located in Arduino Due, This PWM output provides the power switching needed to move the azimuth and elevation control motors. Then the new location of the laser spot on the QD surface has been sensed and updated by QD photo diodes ensuring that the laser spot incident in the center of its surface after this movement.

It was planned for the sensor control algorithm to use a proportional–integral–derivative (PID) like fuzzy logic controllers (FLC) to improve the control performance for a system with noise, a relatively long time of response and the rate of change of this movement depending on how far is the spot located from the center of QD surface. That's happened by getting the feedback position from the QD all the time during its movement. Implementation of the fuzzy logic algorithm that works with 32 bits of precision has been done by using Software codes uploaded from the computer to the microcontrollers by the USB interface.

2) QD Sensor control

In this section, the sensors control part will be discussed covering the Arduino Due microcontroller and its connections with the QD sensor used in this work. The Arduino Due microcontroller pins are introduced as shown in "Fig. 34".

The Arduino Due is a microcontroller board based on the Atmel SAM3X8E ARM Cortex-M3 CPU[18]. It is the first Arduino board based on a 32-bit ARM core microcontroller. It has 54 digital input/output pins (of which 12 can be used as PWM outputs), 12 analog inputs, 4 UARTs (hardware serial ports), a 84 MHz clock, an USB OTG capable connection, 2 DAC (digital to analog), 2 TWI, a power jack, an SPI header, a JTAG header, a reset button and an erase button.

The board contains everything needed to support the microcontroller; simply connect it to a computer with a micro-USB cable or power it with an AC-to-DC adapter or battery to get started. The Due is compatible with all Arduino shields that work at 3.3V and are compliant with the 1.0 Arduino pin out.

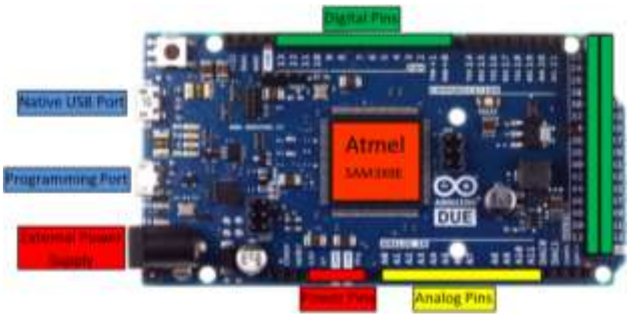

Figure 34. Arduino Due microcontroller

The QD sensor control part offers the readings of the sensors data in real time for the motion sensor because it is supported on a heavy duty pan/tilt tracking platform. This QD sensor is connected to the input/output pins of the Arduino Due microcontroller and the used pins are set to be input pins. The data which are coming from the sensors are analog data then being transferred via the Due controller analog to digital converter into digital data, and then being processed to compute the X and Y ratio to optimize the response of the tracking elevation and azimuth servos.

The Arduino Due microcontroller is attaching the four QD sensor outputs "A, B, C and D" and feeding the power using the 5V and GND pins from the Arduino Due to the read out circuit that were mentioned in the preceding section and to the two servo motors, and is connected to the two servo motors using the PWM digital pins giving them the movement commands as shown in "Fig. 35". The technical specifications of the Arduino Due microcontroller card are listed below in Table V.

TABLE V. ARDUINO DUE SPECIFICATIONS

Microcontroller	AT91SAM3X8E
Operating Voltage	3.3V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	12
Analog Outputs Pins	2 (DAC)
Total DC Output Current on all I/O lines	130 mA
DC Current for 3.3V Pin	800 mA
DC Current for 5V Pin	800 mA
Flash Memory	512 KB all available for the user applications
SRAM	8 KB
Clock Speed	16 MHz
EEPROM	4 KB
Length	1
Width	101.52 mm
Weight	36 g

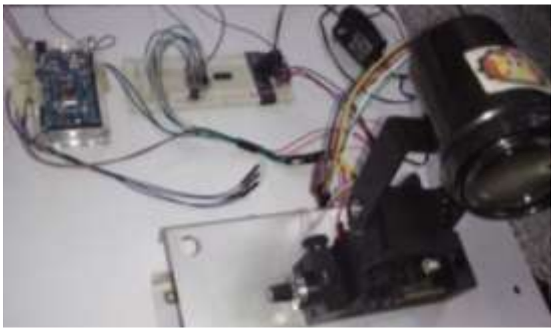

Figure 35. QD Sensor control circuit

3) Arduino programming langue

In this work, Arduino Due microcontroller had been used to achieve certain tasks. The first was the movement control of the two servo motors which was used in the tracking motion control in Azimuth and Elevation. The

second was reading the feedback from QD sensor which was used in the tracking system. The third task is to help the read out circuit in computing the X and Y ratio to optimize the response of the tracking platform that could be used with external programmer for uploading codes. Software codes were uploaded from the computer to the microcontroller by the USB interface, as it was supported by the Arduino microcontroller. The code (Appendix A) was written with the intended proposed system fuzzy (that has been simulated in the previous section) form on the Arduino software that is also known as the Arduino Integrated Development Environment (IDE) as shown in “Fig. 36”.

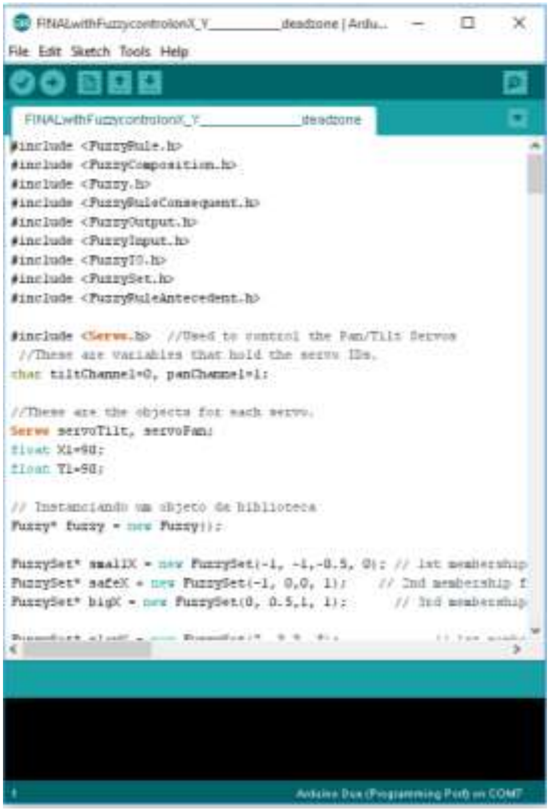

Figure 36. Arduino IDE

G. Conclusion (System performance)

The System performance was measured experimentally in one direction. A high power diode laser was supported on a moving table in the laboratory that is moving in an elevation direction (X), the laser spot was projected to a metal wall as shown “Fig. 37”. The laser source on the moving table was approximately one meter from a metal wall, and the lights were turned off to prevent the overhead lights from producing unwanted noise in the photodetector. The analog output (error signal) from the fuzzy controller and the moving table signals were recorded using an Arduino serial monitor in the computer software.

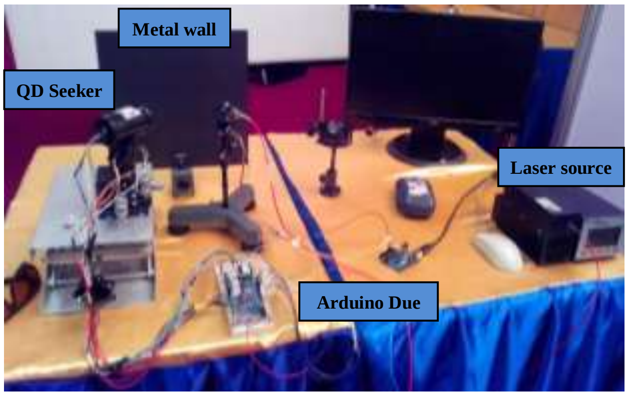

Figure 37. Experimental setup to measure the system performance

The platform tracked satisfactorily, the system performance steadily improved at a distance of 1m (short distance is the worst case of LTS) because further increases would shorten the time used to obtain the derivative data and would make the derivative data unreliable, the system performance was recorded according to the graph in “Fig. 38” .

The maximum speed the laser is able to consistently track at is 15.7 degrees per second. After this point, the laser moves quickly enough that the platform, due to a combination of vibration, friction, and limited field of view, is unable to keep up with the laser image. Although the platform is restricted by the speed with which it can track the laser in a very short distance from the target (1m) which is the worst tracking case, its range of operation is almost unlimited. The target projection angles correspond to an azimuth angle of 180 degrees and to an elevation angle of 180 degrees. The platform is able to track the laser image throughout this entire area - until wall space literally runs out approximately about 20 meters.

Three plots are given in “Fig. 38” which illustrates system performance for the azimuth axis of the tracking platform with the system. All three plots illustrate an analog representation of the motor control signal (the real movement). The reason why the motor control or error signal was chosen to demonstrate system performance is that this signal depicts the fuzzy controller's efforts to align the tracking platform with the laser return and this signal it is direct reflection of the tracking platform's error.

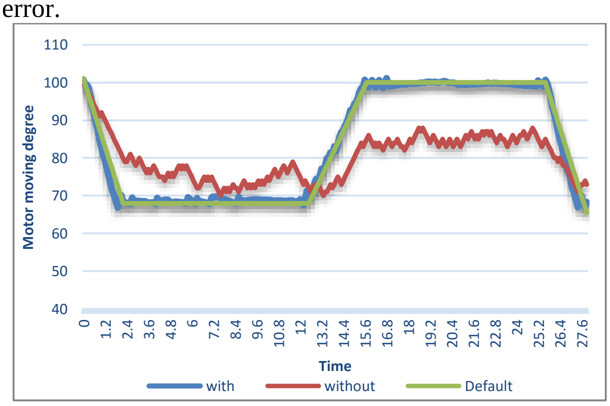

Figure 38. System performance graph

The first plot (green colored) shows the motor control signal for the tracking platform with no target present (default signal) that show the desired movement from degrees between 101 to 68 at a full time from 0 to 27.9 seconds. This plot can be considered a representation of the perfect condition in the tracking platform. There is no transient spikes in this plot could be from a wide range of sources - ambient light impinging upon the photodetector, noise within the signal conditioning circuitry, noise from the fuzzy microcontroller circuitry, and vibration caused by the pulse width modulated motor control signal. This is to be expected, since the platform optics does not have a reflected laser beam from target which it can follow, and the platform remains stationary.

The second plot (red colored) shows the error signal for the tracking platform when the platform is centered on the laser image but without implemented fuzzy controller. The large positive and negative spikes in this plot indicate noise eluded to in the 1st plot in addition the great deal of system vibration. The source of this vibration is most likely the pulse width modulated motor control signals coupled with the extremely sensitive system optics. The platform is constantly trying to reduce its error by aligning itself with the laser image, but in overcoming the limited speed step, the system often misses its target. This missing problem because even very slight movement of the platform causes significant fluctuation of the laser image's position on the sensitive photodetector with a fixed step degree of movement. These changes cause the controller to continually missing the target as it attempts to align the platform with it. Still, however, the control signal trying to be fixed when there is no movement with time because the average platform pointing position is centered on the laser image.

The third plot (blue colored) demonstrates the tracking platform motor control signal with an implemented fuzzy controller algorithm as the platform tracks a laser image that sweeps back and forth through an angle of Approximately 33 degrees on the laboratory wall. The waveform in this plot is the signal which positions the laser optical seeker. This plot shows that the system is able to track a "fast moving" target without any problems with vibration. Notice that in this plot that the motor control signal almost matching with the default signal. Instead, on the downward sweep of the waveform (the laser moves left to right), the motor control signal is predominately negative, and on the upward sweep of the triangular waveform (the laser moves right to left), the motor control signal is predominately positive. This means that the controller is pushing the platform in a direction to match the sweep of the laser to keep the platform aligned with the laser image; the tracking platform is tracking the laser.

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